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# BEST-CHOICE GAMES WHERE ARBITRATION COMES IN (Mathematics of Decision-making under uncertainty)

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# BEST-CHOICE GAMES WHERE ARBITRATION COMES IN

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## 1. Multistage Poker — Simultaneous-Move

We first consider a simple  $n$ -round poker. Each of two players I and II receives a hand  $x$  and  $y$ , respectively, in  $[0,1]$ , according to a uniform distribution, and chooses one of two alternatives Reject or Accept. If choice-pair is R-R, the game proceeds to the next round and both players are dealt new hands  $x$  and  $y$ . If the choice-pair is A-A showdown occurs and the game ends with I's reward  $\text{sgn}(x-y)$ . If players choose different choices, then arbitration comes in, and forces them to take the same choices as I's (II's) with probability  $p$  ( $\bar{p}$ ). This zero-sum game is played in  $n$ -rounds, and player I (II) aims to maximize (minimize) the expected reward to I.

Each of two players must make one choice among two. Players know that arbitration comes in, if their choices are different, and the arbitration is not necessarily fair. Arbitration is made at most in  $n$  times, within which the final decision must be reached. Most of papers [1,2,3,5] analyse a model where arbitration is absent, or fair even if it comes in. We consider in the present article and Ref. [4,6,7] a version of arbitration problems with active and unfair arbitrator who is under the influence of the relative power of the players.

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Let  $\phi_n(x) (\psi_n(y))$  be the probability that player I ( II ) chooses A on the hand  $x (y)$ .

Also let  $v_n$  be the value ( for I ) of the  $n$ -round game. Then we have

$$(1.1) \quad v_n = \max_{\phi_n(\cdot)} \min_{\psi_n(\cdot)} E_{x,y} [(\bar{\phi}_n(x), \phi_n(x)) M_n(x,y) (\bar{\psi}_n(y), \psi_n(y))^T]$$

where

$$(1.2) \quad M_n(x,y) = \begin{matrix} & \begin{matrix} R & A \end{matrix} \\ \begin{matrix} R \\ A \end{matrix} & \begin{bmatrix} v_{n-1} & \bar{p} \operatorname{sgn}(x-y) + p v_{n-1} \\ p \operatorname{sgn}(x-y) + \bar{p} v_{n-1} & \operatorname{sgn}(x-y) \end{bmatrix} \end{matrix}$$

It is clear that

$$(1.3) \quad v_n - v_{n-1} = \max_{\phi} \min_{\psi} A_n(\phi, \psi), \quad \text{with}$$

$$(1.4) \quad A_n(\phi, \psi) \equiv E [(\bar{\phi}, \phi) (\operatorname{sgn}(x-y) - v_{n-1}) \begin{bmatrix} 0 & \bar{p} \\ p & 1 \end{bmatrix} (\bar{\psi}, \psi)^T] \\ = E [(\operatorname{sgn}(x-y) - v_{n-1}) (p\phi + \bar{p}\psi)],$$

where  $\phi_n(x)$  and  $\psi_n(y)$  in (1.3)-(1.4) are abbreviated by  $\phi$  and  $\psi$ . We repeatedly use this simplification throughout this paper.

Theorem 1. The solution to the  $n$ -round poker (1.1)-(1.2) is :

$$(1.5) \quad \phi_n^*(x) = I(x > a_n), \quad \psi_n^*(y) = I(y > \bar{a}_n), \quad \text{and} \quad v_n = 2a_{n+1} - 1, \\ \text{where } \{a_n\} \text{ satisfies the recursion}$$

$$(1.6) \quad a_{n+1} = a_n + \frac{1}{2} (p \bar{a}_n^2 - \bar{p} a_n^2) \quad (n \geq 1, a_1 = 1/2)$$

As  $n$  tend to  $\infty$ , we have

$$(1.7) \quad a_n \uparrow \alpha = \frac{\sqrt{p}}{\sqrt{p} + \sqrt{\bar{p}}} \quad \text{and} \quad v_n \uparrow 2\alpha - 1 = \frac{\sqrt{p} - \sqrt{\bar{p}}}{\sqrt{p} + \sqrt{\bar{p}}}$$

Proof is omitted.

The limit  $v_\infty = \frac{\sqrt{p} - \sqrt{\bar{p}}}{\sqrt{p} + \sqrt{\bar{p}}}$  is, as a function of  $p \in [\frac{1}{2}, 1]$ , convex and increas-

ing with values 0 at  $p = 1/2$ , and 1 at  $p = 1$ .

Corollary 1.1 If  $p = 1/2$  then  $a_n = 1/2$  and  $v_n = 0$ ,  $\forall n \geq 1$ .

If  $p = 1$ , then  $a_{n+1} = \frac{1}{2}(1 + a_n^2)$  (i.e., Moser's sequence) and  $v_n = a_n^2$

In Table 1, the values of the game for various  $p$  and  $n$  are given.

Table 1. Values of the game for various  $p$  and  $n$ .

	$p=0.5$	$p=0.6$	$p=0.8$	$p=1$			
	$a_n$	$v_n$	$a_n$	$v_n$	$a_n$	$v_n (=a_n^2)$	
$n=1$	0.5	0.25	0.5	0.15	0.5	0.25	
2	.525	.2752	.575	.2284	.625	.3906	
3	$\left[ \begin{array}{l} a_n = \frac{1}{2} \\ v_n = 0 \\ \forall n \geq 1 \end{array} \right]$	.5376	.0878	.6142	.2720	.6953	.4834
4		.5439	.0942	.6360	.2971	.7417	.5501
5		.5471	.0975	.6486	.3119	.7757	.6008
6		.5488	.0993	.6559	.3205	.8004	.6406
$\vdots$		$\vdots$	$\vdots$				

## 2. Multistage Poker — Bilateral-move.

We investigate in this section the bilateral-move variant of the poker discussed in the previous section. Players act not simultaneously but consecutively, i.e., player I acts first and then player II acts, after knowing his rival's choice of either R or A. Denote this  $n$ -round poker by  $G_n$ , and let  $w_n$  be the value of  $G_n$ . The game would be conveniently described by

Player	Hand	1 st step	2 nd step	Payoff to I
I	$x$	$\begin{cases} R \\ A \end{cases}$	$\begin{cases} R \text{ ----- } w_{n-1} \\ A \text{ ----- } pw_{n-1} + \bar{p} \operatorname{sgn}(x-y) \end{cases}$	
II	$y$		$\begin{cases} R \text{ ----- } p \operatorname{sgn}(x-y) + \bar{p} w_{n-1} \\ A \text{ ----- } \operatorname{sgn}(x-y) \end{cases}$	

Let  $\phi_n(x)$  be the probability that I chooses A when his hand is  $x$ . Also let  $\psi_{Rn}(y)$  ( $\psi_{An}(y)$ ) be the probability that II chooses A when his hand is  $y$  and his rival's choice has been R (A). The expected payoff to I when players use the strategy-triple  $\phi_n - \psi_{Rn} - \psi_{An}$  is

$$(2.1) \quad M_n(\phi, \psi_R, \psi_A) = E_{x,y} \left[ w_{n-1} \bar{\phi} \bar{\psi}_R + (p w_{n-1} + \bar{p} \operatorname{sgn}(x-y)) \bar{\phi} \psi_R \right. \\ \left. + (p \operatorname{sgn}(x-y) + \bar{p} w_{n-1}) \phi \bar{\psi}_A + \operatorname{sgn}(x-y) \phi \psi_A \right] \\ = w_{n-1} + E \left[ (\operatorname{sgn}(x-y) - w_{n-1}) \{ p \phi + \bar{p} (\bar{\phi} \psi_R + \phi \psi_A) \} \right],$$

where  $\phi_n(x)$ ,  $\psi_{Rn}(y)$  and  $\psi_{An}(y)$  are simply written by  $\phi$ ,  $\psi_R$  and  $\psi_A$ , respectively.

The Optimality Equation we want to discuss is

$$(2.2) \quad w_n = \max_{\phi} \min_{\psi_R, \psi_A} M_n(\phi, \psi_R, \psi_A), \quad (n \geq 1, w_0 = 0).$$

Theorem 2. The case where  $\frac{1}{2} < p < 1$ . Determine the three sequences by

$$(2.3) \quad b_n = \frac{1}{2} \left[ 1 + \frac{2p w_{n-1}}{\bar{p}(w_{n-1})^2 + 3p - 1} \right],$$

$$(2.4) \quad r_n = \frac{1}{2} \bar{w}_{n-1} b_n,$$

$$(2.5) \quad \bar{a}_n = \frac{1}{2} (1 + w_{n-1}) \bar{b}_n \quad (n \geq 1; w_0 = 0)$$

Then  $0 < r_n < b_n < a_n < 1, \forall n \geq 1$ , and the optimal strategy-triple is

$$\phi_n^*(x) = I(x > b_n), \quad \psi_{Rn}^*(y) = I(y > r_n), \quad \psi_{An}^*(y) = I(y > a_n).$$

The value  $w_n$  of the game  $G_n$  is given by the recursion (2.13) given below.

Proof is omitted.

The two extreme cases are discussed in the following. Proofs are omitted.

Theorem 3. The case  $p = \frac{1}{2}$ . Let  $c_{n-1} = \frac{1+w_{n-1}}{1-w_{n-1}} \in (0, 1)$ . Determine the three sequences  $\{r_n\}, \{a_n\}$  and  $\{w_n\}$  by

$$(2.14) \quad \bar{a}_n = \frac{1+w_{n-1}}{2(1+c_{n-1}^2)}, \quad r_n = c_{n-1} \bar{a}_n \quad (0 < r_n < a_n < 1, \forall n)$$

and

$$(2.15) \quad w_n = w_{n-1} - \frac{1}{2} \left\{ (w_{n-1} + r_n) \bar{r}_n - (\bar{a}_n)^2 \right\}.$$

The solution to the game is

$$\phi_n^*(x) = \begin{cases} 0 & \text{if } x \leq r_n \\ \text{arbitrary in } [0, 1], & \\ \text{but satisfies } \int_{r_n}^{a_n} \phi_n^*(x) dx = \bar{a}_n / c_{n-1}, & \text{if } r_n \leq x \leq a_n \\ 1 & \text{if } x \geq a_n \end{cases}$$

$$\psi_{Rn}^*(y) = I(y > r_n), \quad \text{and} \quad \psi_{An}^*(y) = I(y > a_n),$$

and the value of the game is  $w_n$ . Moreover  $w_n \downarrow w_\infty$  as  $n \rightarrow \infty$ , and  $w_\infty$  is given by (2.22).

$$\left[ \text{e.f. (2.22) is } w_\infty = - \left[ 1 - \left( \frac{\sqrt{5}-1}{2} \right)^{1/2} \right] / \left[ 1 + \left( \frac{\sqrt{5}-1}{2} \right)^{1/2} \right] \doteq -0.1197. \right]$$

Theorem 4. The solution to the game for  $p = 1$ . The optimal strategy for I is "Choose A ( R ), if  $x > (<) \frac{1}{2}(1+w_{n-1})$ ", where  $\{w_n\}$  is determined by the recursion

$$w_n = \frac{1}{4} (1 + w_{n-1})^2, \quad (n \geq 1; \quad w_0 = 0)$$

Player II always chooses R until the game is stopped by I.

Remark 1. We can show after some algebra that (2.4)-(2.5), in Theorem 2, when  $p \downarrow 1/2$ , become (2.14) in Theorem 3. Also, it is easy to find, from (2.15) and (2.21), that

$$(2.23) \quad w_n = - \frac{1 + c_{n-1}^2 - c_{n-1}^4}{2(1 + c_{n-1})^2(1 + c_{n-1}^2)} \quad (n \geq 1, w_0 = 0, c_0 = 1)$$

It is a surprising result that  $w_n \downarrow w_\infty$ , and the limit is different from  $-1$  and  $0$ . The disadvantage for the first-mover which is unavoidable from leaking some information about his private hand  $x$ , does not increase to its extreme and stops at an intermediate point by making a skillful bluff.

Computation of the values which appear in Theorem 3 is shown in Table 2.

Table 2. Solution of the bilateral poker for  $p = 1/2$ .

	$r_n$	$a_n$	$B_n$	$w_n$	$c_n$
$n=1$	$1/4$	$3/4$	$1/4$	$-0.0625 (= -1/16)$	$0.8824$
2	$0.2326$	$0.7364$	$0.2973$	$-0.0930$	$.8298$
3	$.2229$	$.7314$	$.3237$	$-0.1074$	$.8060$
4	$.2181$	$.7295$	$.3357$	$-0.1141$	$.7952$
5	$.2158$	$.7286$	$.3412$	$-0.1171$	$.7903$
6	$.2148$	$.7283$	$.3438$	$-0.1185$	$.7881$
7	$.2143$	$.7281$	$.3450$	$-0.1192$	$.7870$
8	$.2140$	$.7280$	$.3456$	$-0.1195$	$.7865$
9	$.2139$	$.7280$	$.3458$	$-0.1196$	$.7863$
10	$.2139$	$.7280$	$.3459$	$-0.1197$	$.7862$
11	$.2139$	$.7280$	$.3459$	$-0.1197$	$.7862$
$\vdots$					
Limit	$0.2139$	$0.7280$	$0.3460$	$-0.1197$	$0.7862$

Remark 2. When  $p=1$  the game value  $w_n$  is equal to the game value  $v_n$  in the simultaneous-move version of this poker. Because, as was shown by Corollary 1.1, .....

### 3. Final Remark.

From Theorem 2 we show a computation of the solution of the bilateral poker for  $p = 0.55$  (0.8) in Table 3 (4) for very small  $n$ . It is instructive to compare these values with those appearing in Tables 1 and 2. (Tables 3 and 4 are omitted.)

Theorem 2 gives a result that if  $p = 0.6$ , then

$$r_n = \frac{1}{4}, \quad b_n = \frac{1}{2}, \quad a_n = \frac{3}{4}, \quad w_n = 0, \quad \text{for all } n \geq 1.$$

This implies that the disadvantage for I, which is inevitable due to his "moving-first" disappears if  $p = 0.6$ .

The values of bilateral poker for various  $p \in [\frac{1}{2}, 1]$  are compared in Figure 2. Curves (a), (b), (c), (d), and (e) are for  $p = 0.5, 0.55, 0.6, 0.8$ , and 1, respectively.

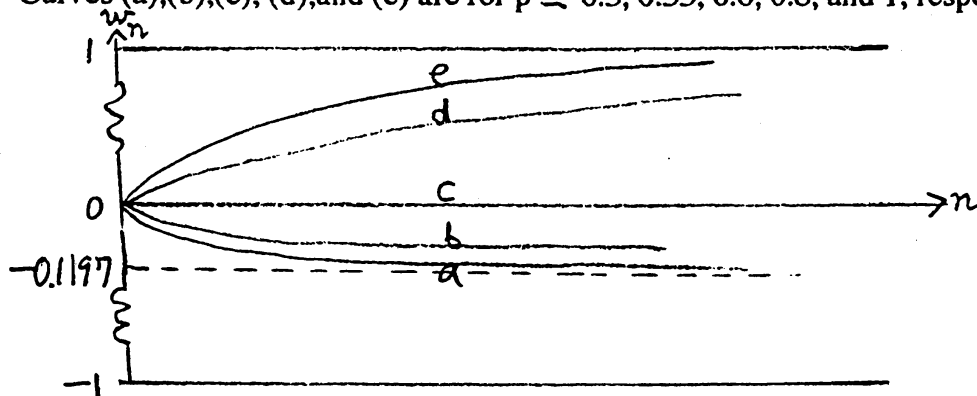


Figure 2. Values of bilateral poker for various  $p$

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